Annales de Chimie - Science des Matériaux
Vol. 50, No. 1, February, 2026, pp. 73-85
Journal homepage: http://iieta.org/journals/acsm

Experimental and Statistical Assessment of Sand Concrete Incorporating Ceramic Waste Sand

Nouha Rezaiguia[1,2], Nedjma Meziani[3], Houria Hebhoub[1,2], Laidi Babouri[4,5], Fouad Boukhelf[6*]

[1] Department of Civil Engineering, Faculty of Technology, 20 August 1955 University, Skikda 21000, Algeria
[2] LMGHU Laboratory, 20 August 1955 University, Skikda 21000, Algeria
[3] Department of Hydraulic and Civil Engineering, Faculty of Applied Sciences, University of Kasdi Merbah, Ouargla 30000, Algeria
[4] Department of Physics and Chemistry, Normal Higher School of Technological Education of Skikda, Skikda 21000, Algeria
[5] Laboratoire d'Anticorrosion, Matériaux, Environnement et Structures, Université du 20 Août 1955-Skikda, Skikda 21000, Algérie
[6] Institut de Recherche de la Construction - ESTP, Cachan F-94234, France

Corresponding Author Email: fboukhelf@estp.fr

https://doi.org/10.18280/acsm.500108

Received: 12 November 2025
Revised: 17 December 2025
Accepted: 22 December 2025
Available online: 28 February 2026

Keywords:
sand concrete, ceramic waste, valorization, mechanical and physical properties, response surface analysis, factorial design

ABSTRACT

This study examines the use of ceramic waste sand (CWS) as a partial substitute for natural dune sand (DS) in sand concrete. Five levels of volumetric substitution of sand (0%, 10%, 20%, 40%, and 60%) were studied to evaluate their effects on fresh properties (workability, density, and air content) and hardened properties (compressive strength, flexural strength, modulus of elasticity, and ultrasonic pulse velocity). The results reveal that replacing DS with CWS improves fresh state and mechanical performance. Slump increased from 21.5 cm to 26.2 cm for concrete containing 0% and 60% of CWS, reflecting improved workability due to better particle settling and reduced water absorption. Compressive and flexural strengths increased at 28 days from 28.5 MPa and 6.1 MPa to 34.2 MPa and 8.6 MPa, respectively, for the concrete containing 0% and 40% of CWS. The optimum mechanical performance was achieved between 20% and 40% substitution. Beyond this range, an increase in performance was observed. The statistical modeling using a full factorial design and response surface methodology (RSM) provided predictive equations validated by the analysis of variance (ANOVA) ($p < 0.05$; R^2 up to 0.972), confirming the robustness and accuracy of the models. Findings highlight the technical feasibility of using CWS as a high-performance, eco-efficient alternative to natural sand, thereby promoting large-scale recycling of ceramic waste in concrete production.

1. INTRODUCTION

Growing concerns about the depletion of natural resources, in particular sand resources, represent a major environmental and economic challenge for the construction industry. The intensive extraction of natural sand has significant impacts, including soil erosion, environmental degradation, and disruption of ecosystems [1-3]. In the context of the current environmental and social crises, recycled materials are emerging as a sustainable alternative that not only reduces pressure on resources but also supports the development of a circular economy [4, 5].

One of the most promising recycled materials in this area is ceramic waste, generated primarily during the manufacture, forming, and demolition of products such as tiles, bricks, and sanitary equipment. Given their mineralogical composition rich in silica and alumina, compatibility with hydraulic binders, and potential pozzolanic properties, these materials are particularly promising candidates for partially replacing cement or natural aggregates in concrete [6, 7].

Recent studies have examined their use in construction materials, confirming their technical and environmental potential. Barreto et al. [8] showed that ceramic waste can be used as a pozzolanic constituent, replacing up to 20% of Portland cement without compromising mechanical strength. Juan-Valdés et al. [9] showed that incorporating ceramic materials from construction and demolition waste can produce high-performance recycled concrete using both coarse ceramic aggregates and brick powder as pozzolanic additives, while mechanical and microstructural properties are similar to those of ordinary concrete. This approach highlights the potential of recycled ceramics for sustainable recovery within a circular economy.

In addition, Silva and De Melo [10] studied the effect of ceramic waste as aggregate and the partial substitution of cement with ceramic powder. Due to its pozzolanic effect, ceramic powder contributes to optimizing various properties of concrete, including workability, freeze-thaw resistance, and electrical resistivity. However, Meena et al. [11] reported that excessive ceramic content can reduce compressive strength. According to Joshi and Parekh [12], powder derived from ceramic waste has significant potential as a partial substitute for cement in self-compacting concrete, thereby helping to reduce the environmental impact of the sector. This secondary material reduces the demand for natural resources and lowers the demand for cement.

Ceramic waste can also be used as recycled aggregate in concrete, improving workability while maintaining and increasing compressive strength and water penetration resistance [13]. Furthermore, studies conducted by Handel et al. [14] and Jwaida et al. [15] have confirmed that incorporating ceramic and glass waste as a partial replacement of cement and aggregates reduces environmental impact, conserves natural resources, and produces lightweight concrete with satisfactory mechanical properties. More recently, Ocampo et al. [16] highlighted the versatility of ceramic waste, which can also be used in other industrial applications such as the manufacture of electrical insulation, alumina extraction, and nuclear waste immobilization.

However, few studies have systematically evaluated the effect of replacing natural sand with recycled ceramic waste sand (CWS) on a comprehensive set of physical and mechanical properties of sand concrete, based on a combination of experimental testing and advanced statistical modeling. In fact, no research has implemented a full factorial design combined with a response surface methodology (RSM) to optimize the performance of concrete sand incorporating ceramic waste sand.

RSM is a robust optimization tool that is widely used in engineering. It enables modeling, prediction, and performance improvement based on multiple variables while minimizing the number of experimental tests [17-19]. The application of this tool to waste-incorporated concrete enables the identification of optimal formulations that balance mechanical performance, durability, and reduced environmental impact [20, 21].

This study aims to fill a gap in research by systematically examining the effect of volumetric replacement of DS with CWS on the properties of sand concrete in its fresh state (workability, density, and air content) and in its hardened state (compressive strength, flexural strength, modulus of elasticity, and ultrasonic wave velocity). In order to identify the optimal limit beyond which the physical and mechanical properties of sand concrete tend to decrease, five replacement ratios were chosen (0%, 10%, 20%, 40%, and 60%) to cover a wide range of substitution levels. These values are consistent with previous studies on the use of ceramic waste as a substitute for fine aggregates, thus ensuring both the comparability of results and the experimental design's representativity. This work includes a comprehensive experimental program and a statistical modeling approach based on RSM. The use of statistical modeling using the RSM method enabled not only the quantification of the effect of the substitution rate of DS by CWS, but also the identification of general trends governing the evolution of sand concrete properties. This approach offers a dual advantage by reducing the number of experimental tests required using reliable predictive models and facilitating the optimization of formulations by highlighting interactions between variables. This combination helps to develop reliable predictive models validated by analysis of variance (ANOVA) and provides valuable information for designing more efficient and sustainable sand-based concretes. However, due to the complexity of the experimental program and the high number of interacting parameters and variables, a single-response optimization was adopted instead of a multi-response approach, ensuring greater accuracy in capturing the overall behavior of the material.

2. MATERIALS AND METHODS

2.1 Raw materials

The raw materials used in this study are shown in Figure 1. Portland composite cement (CPJ–CEM II 42.5 S-L), supplied by the Hadjar Essoud cement plant (Skikda, Algeria), was used as the main binder. This cement has an absolute density of 3.230 g/cm³ and complies with the requirements of standard EN 197-1 for CEM II type cements. The fine aggregates consisted of two types of sand: natural dune sand (DS) of a siliceous nature and 0/1 particle size class, sourced from the Oued Z'hor quarry, east of Skikda, and recycled sand from ceramic waste (CWS) of 0/4 particle size class, produced by grinding and screening ceramic sink scraps. A fine addition of limestone (L), collected from the filtration units of the Ben Azzouz quarry (east of Skikda), was also incorporated into the matrix. More than 80% of the limestone filler particles are less than 80 µm, which helps to improve the densification of the matrix. A high-performance water-reducing admixture, Master Glenium 26 (SP), was used to improve the workability of the mixtures without increasing the water/cement ratio. This is a polycarboxylate ether-based superplasticizer, supplied as a light brown liquid with a pH of 5.0 and a density of 1.07 g/cm³. Finally, tap water was used to mix all concrete formulations.

Figure 1. Raw materials used: (a) dune sand (DS); (b) ceramic waste sand (CWS), and (c) limestone filler (L)

Table 1 shows the main physical and chemical properties of the fine aggregates used. These data provide the basic characteristics needed to understand the influence of each component on the fresh and hardened properties of the sand concrete. The results presented in Table 1 reveal distinct physicochemical differences between the materials studied. DS has a mainly siliceous SiO_2 composition of 94.09% and a density of 2.630 g/cm³, while CWS is characterized by a significantly higher alumina Al_2O_3 content of 22.3% and a slightly lower density (around 2.435 g/cm³) than DS. The sand equivalent value of CWS and DS is 86% and 75%, respectively, indicating a higher level of cleanliness and lower clay content in the recycled ceramic material. The fineness modulus of CWS and DS are 3.12 and 1.6, respectively, thus suggesting that its incorporation may improve particle settling and potentially enhance the mechanical performance of sand concrete. In addition, CWS has a slightly lower water absorption of 2.80% compared to 3.21% for DS and a lower content of fines less than 80µm of 3.33% compared to 6.67%

for DS, reflecting a less porous and more resistant aggregate.

The results presented in Table 1 reveal distinct physicochemical characteristics among the investigated materials. DS exhibits a high siliceous composition SiO_2 of 94.09% and an absolute density of 2.630 g/cm³, whereas CWS is distinguished by a remarkable alumina content Al_2O_3 of 22.3% and a slightly lower absolute density of 2.435 g/cm³. The sand equivalent value of CWS and DS are 86% and 75%, respectively, indicating the higher cleanliness of the recycled ceramic material. The fineness modulus of CWS and DS is 3.12 and 1.6, respectively, suggesting that their incorporation can enhance packing density and improve mechanical strength. Furthermore, CWS exhibits slightly lower water absorption of 2.80% compared to 3.21% for DS, as well as a reduced fines content of 3.33% vs. 6.67% for DS, reflecting a less porous and more stable material.

The limestone filler (L) confirms its carbonate nature with a $CaCO_3$ content of 84.60%, making it a suitable mineral additive for matrix densification. These differences indicate a complementary interaction between the materials, which can be exploited to optimize the formulation of durable, high-performance cementitious composites. Finally, the use of Master Glenium 26 superplasticizer (pH = 5.0, density = 1.070 g/cm³) allows for precise adjustment of the rheology of the mixture while maintaining mechanical strength and durability.

Table 1. Physical and chemical properties of sands

Physical Properties		
	DS	**CWS**
Bulk density (g/cm³)	1.530	1.188
Density (g/cm³)	2.630	2.435
Sand equivalent (%)	75	86
Water absorption (%)	3.21	2.80
Fineness modulus (%)	1.55	3.14
Fines content (%)	6.20	5
Chemical Composition (%)		
SiO_2	94.09	70.6
Al_2O_3	2.36	22.3
Fe_2O_3	1.15	1.75
CaO	0.80	1.36
MgO	0.14	0.25
SO_3	0.01	0.08
K_2O	0.58	2.17
Na_2O	0.20	1.50

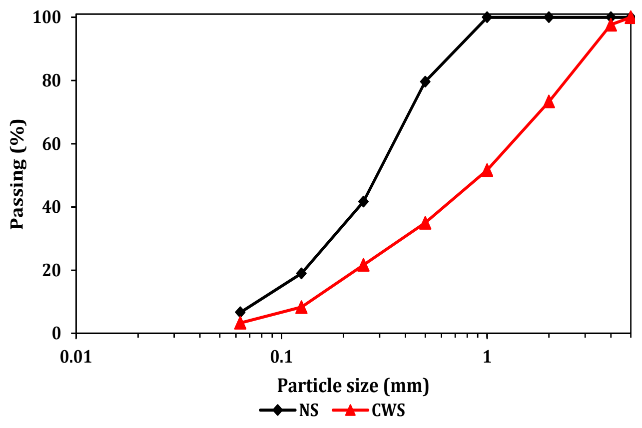

Figure 2. Particle size distribution of sands used

Figure 2 shows the particle size distribution curves for DS and CWS. DS is a siliceous material with a particle size of 0/1 mm and a fine grain size, with more than 80% of particles passing through a 0.5 mm sieve. This narrow distribution results in a low fineness modulus, limited compaction density, and higher water demand. Meanwhile, CWS has a granular class of 0/4 mm and a larger particle size distribution with a significant proportion of coarse particles (ranging from 1 mm to 4 mm). This better granular distribution promotes particle compaction, reduces voids, and strengthens the granular structure, thus contributing to the optimization of the internal structure and potentially improving the mechanical performance and durability of sand concrete [22].

2.2 Experimental program

The experimental program consisted of partially replacing DS with CWS in the composition of sand concrete, at volumetric substitution rates of 0%, 10%, 20%, 40%, and 60%. These replacement rates were chosen to cover a wide range of substitutions while remaining compatible with technical feasibility and current industrial practices. The main objective of this study is to evaluate the influence of CWS incorporation on the fresh properties (workability, bulk density, and entrained air content) and hardened properties (compressive strength, flexural strength, modulus of elasticity, and ultrasonic pulse velocity) of sand concrete. The reference mix (SC0) was designed according to the experimental procedure established in the Sablocrete project as reported in the work of Chanvillard and Basuyaux [23], whereas the other mixes (SCCW) were prepared by gradually replacing the natural DS with recycled ceramic sand (CWS) in the reference formulation. For all mixtures, several parameters were kept constant, including a water/cement ratio (W/C) set at 0.68. This value was chosen to ensure adequate workability of the sand concrete, which is characterized by a very fine granular structure and a large specific surface area. The selected W/C ratio complies with the sand concrete formulation principles proposed by Chanvillard and Basuyaux [23], which recommend relatively high-water contents for concrete incorporating DS. Maintaining a constant W/C ratio in all mixtures made it possible to evaluate in isolation the effect of replacing DS with ceramic CWS on the properties of fresh and hardened concrete. In addition, the use of a high water-reducing polycarboxylate-based superplasticizer (SP) at a dosage of 0.9% by weight of cement made it possible to obtain a satisfactory consistency while limiting the negative effects of the relatively high-water content on mechanical performance, as shown in previous studies on fine-grained concretes. The detailed proportions of the mixture are shown in Table 2.

In order to characterize the properties of sand concrete in its fresh and hardened states, a series of standardized tests was carried out. The fresh state tests included measuring the fresh density, carried out in accordance with standard NF EN 12350-6, to assess the compactness of the mixture and verify its conformity. Workability was evaluated using the Abrams cone slump test, in accordance with standard NF EN 12350-2, which indicates the consistency of the concrete and its ease of placement. In addition, the air content was determined using a pressure air meter, in accordance with standard NF EN 12350-7, which made it possible to quantify the volume of air in the mixture, a parameter known to influence both durability, particularly against freeze-thaw cycles, and mechanical performance. For the hardened state, prismatic specimens measuring 4 × 4 × 16 cm³ were cast in the laboratory at a temperature of 25 °C and relative humidity of 50% and hardened in water until the test was completed. The flexural strength was determined using a three-point flexural test in accordance with standard NF EN 196-1, after which the resulting half-specimens were subjected to a compression test, which allowed the flexural and compressive strengths to be evaluated simultaneously. The modulus of elasticity at 28 days was estimated using the empirical relationship proposed by Neville [24], which correlates the compressive strength and stiffness of the material. Finally, the internal quality and homogeneity of the concrete were evaluated using ultrasonic pulse velocity (UPV) measurements, performed on 15 × 15 × 15 cm³ cubic specimens after 28 days of curing in water, in accordance with standard NF EN 12504-4.

Table 2. Mix proportions of different concrete mixtures (kg/m^3)

	Substitution Rate (%)	CEM II	DS	CWS	SP	L	W
SC0	0%	400	1193.0	-	3.89	251.6	272
SCCW10	10%	400	1073.7	110.5	3.89	251.6	272
SCCW20	20%	400	954.4	220.9	3.89	251.6	272
SCCW40	40%	400	715.8	441.8	3.89	251.6	272
SCCW60	60%	400	477.2	662.7	3.89	251.6	272

2.3 Statistical analysis and validation of response surface method models

2.3.1 Statistical modeling

In order to evaluate the substitution effect of DS by CWS on the performance of sand concrete, to identify the interactions between variables, and to optimize the mechanical and physical properties, statistical modeling was performed using RSM, based on a full factorial design. The experimental data were adjusted using least-squares regression to establish a polynomial model representing the material's behavior. This model's validity has been checked using analysis of variance (ANOVA) and prediction graphs. Finally, a comparison between the experimental results and the predicted values made it possible to evaluate the accuracy of the model and determine the optimal conditions.

2.3.2 Parameter estimation using the least squares method

The least squares method allows a mathematical model to be fitted with experimental data by minimizing the deviation between observed values and those predicted by the model [25]. Furthermore, the factorial design is an appropriate methodology for conducting experimental tests in a systematic manner, allowing the effects of different variables and their interactions to be evaluated. This approach is particularly useful in contexts where several factors may influence the measured response, and its ability to isolate individual effects is a major advantage in statistical research [26]. The experimental results can be expressed using the following mathematical Eq. (1):

$$Y = \beta_0 + \beta_1 X \quad (1)$$

where, Y, X, and $\beta_{0,1}$ are the response (e.g., strength, slump, etc.), the independent variables of studied factors (substitution rate in our case), and the model coefficients, estimated using the least squares method, respectively.

3. RESULTS AND DISCUSSION

3.1. Fresh state properties

3.1.1 Workability

Figure 3 shows a progressive increase in slump, from 20.50 cm for the SC0 to 26.83 cm for SCCW60. This improvement is mainly attributed to the favorable particle size distribution of CWS, which reduces internal friction and improves the fluidity of the mixture [27]. In addition, the low water absorption capacity of CWS may help to preserve a greater amount of free water in the paste, thus further increasing fluidity [28]. Nevertheless, these results do not agree with those of Ellatief et al. [29] and Jain et al. [30]. This may be due to the use of plasticizing admixtures in the present study, which are designed to maintain adequate consistency, especially at higher substitution levels. Finally, the linear regression equation derived (y = 1.517x + 19.537) confirms, with a high correlation coefficient (R^2 = 0.967), the significant influence of the CWS substitution rate on workability.

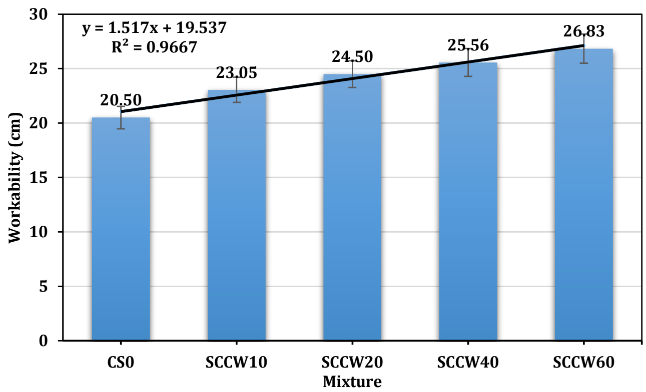

Figure 3. Effect of ceramic waste sand (CWS) on the workability of the sand concrete studied

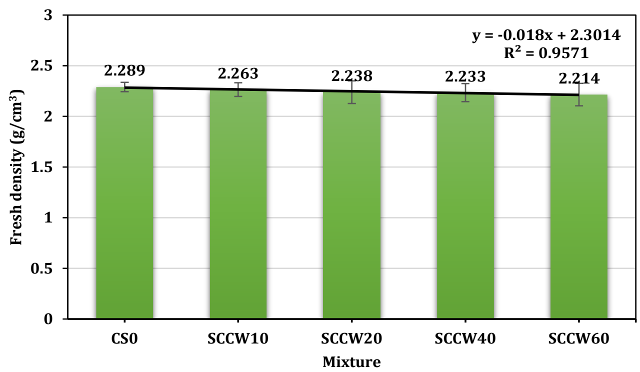

Figure 4. Effect of ceramic waste sand (CWS) on the fresh density of the sand concrete studied

3.1.2 Density

The analysis of the fresh density of sand concrete as a function of the replacement rate with CWS is shown in Figure

4. The apparent density decreases from 2.289 g/cm³ for the reference concrete SC0 to approximately 2.214 g/cm³ for SCCW60. This reduction is mainly attributed to the lower density of CWS compared to DS, which contributes to reducing the total weight of the material [15, 31]. The strong linear relationship is modeled by the regression equation ($y = -0.018x + 2.3014$), with a correlation coefficient $R^2 = 0.957$. From a technical point of view, this density reduction highlights the potential of incorporating CWS in the production of lightweight structural concrete.

3.1.3 Air content

Figure 5 shows the air content in sand concrete as a function of the CWS rate. An increase is observed from 4.90% for SC0 to 6.50% for SCCW60. This may be attributed to the irregular shape and specific particle size distribution of the CWS particles, which promote air retention in the mixture [11]. In addition, the angular nature of CWS particles can create localized areas of air entrapment during mixing [32, 33]. The linear correlation with a very high correlation coefficient $R^2 = 0.983$, expressed by the regression equation ($y = 0.39x + 4.61$), confirms the direct relationship between the substitution rate and the increase in air content. Despite this moderate increase, it can affect the compactness of the concrete and must therefore be considered in the mix design to ensure that the mechanical performance and durability of the material are maintained.

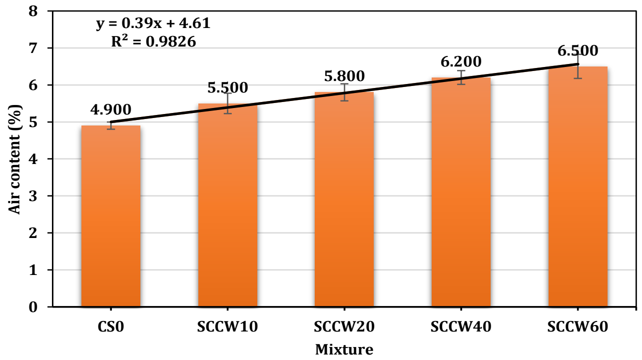

Figure 5. Effect of CWS on the air content of the sand concrete studied

3.2. Mechanical properties

3.2.1 Compressive strength

The compressive strengths at 7, 28, and 90 days of the sand concretes studied are shown in Figure 6. From 7 to 90 days, compressive strength increases, with a more pronounced increase observed between 28 and 90 days. At 7 days, the variations between the mixtures remain limited, although the 20% to 40% substitutions show a slight advantage, attributed to the angular morphology and surface roughness of the CWS particles, which improve the interfacial bonding between the paste and the aggregates. After 28 days, all mixtures show an increase in strength, particularly the 20% and 40% substitution levels. This is due to the high silica (SiO_2) content in the chemical composition of CWS, which promotes the formation of additional C-S-H from the pozzolanic reaction between silica and Portlandite, thus densifying the cement matrix [34, 35]. At 90 days, the SCCW60 mixture achieved the highest compressive strength, closely followed by the 40% and 20% substitution levels. Higher substitution rates lead to continuous performance improvements compared to the CS0, with performance gains of 16.6%, 25.1%, and 29.4% recorded at 7, 28, and 90 days, respectively, for the SCCW60. These results are consistent with the literature [36-38]. Therefore, the incorporation of CWS allows a significant proportion of DS to be replaced while maintaining mechanical performance.

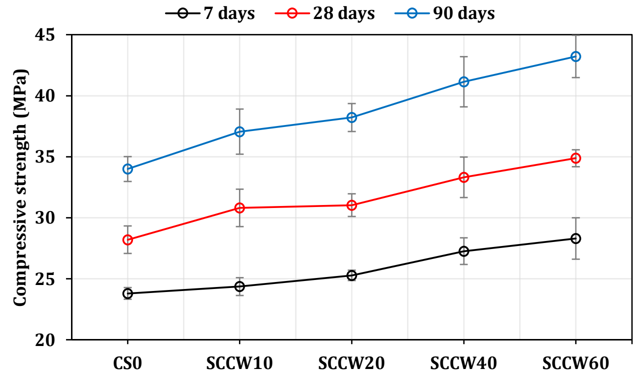

Figure 6. Effect of CWS on the compressive strength at 7, 28 and 90 days of the sand concrete

3.2.2 Flexural tensile strength

The flexural strengths of the sand concretes studied at 7, 28, and 90 days are shown in Figure 7. The results show that incorporating CWS improves the flexural strength of sand concrete at all ages. Higher substitution rates lead to continuous performance improvements compared to the CS0, with performance gains of 93.6%, 78.8%, and 61.7% recorded at 7, 28, and 90 days, respectively, for the SCCW60. This improvement is attributed to the angular shape and hardness of CWS particles, which densify the granular skeleton and reinforce the interfacial transition zone (ITZ) [39, 40]. In addition, the presence of fine silica-rich CWS particles can create a pozzolanic effect, generating additional CSH and retaining water, thus promoting better cement hydration and contributing to favorable mechanical performance [34, 41].

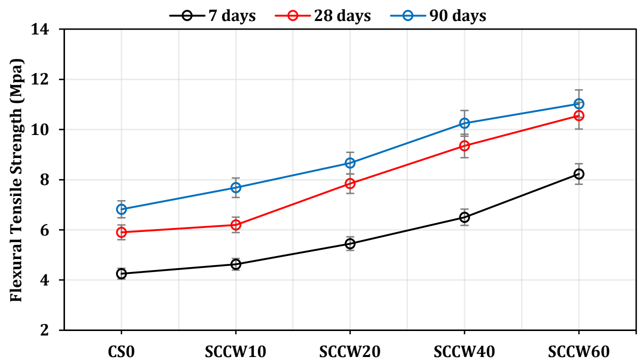

Figure 7. Effect of CWS on the flexural tensile strength at 7, 28 and 90 days of the sand concrete studied

3.2.3 Elasticity modulus

Figure 8 shows an increase in the elastic modulus at 28 days with higher CWS rate. Compared to CS0, mixes with 10%, 20%, 40%, and 60% of CWS showed increases in elastic modulus of 4.5%, 6.8%, 8.4%, and 8.9%, respectively. This improvement can be attributed to the pozzolanic effect of CWS and their angular shape, which promotes good adhesion with the cement matrix. The denser and more homogeneous structure resulting from this substitution improves the overall stiffness of the material, as reflected in the increase in elastic modulus [42]. These results are in good agreement with the literature [40] and confirm that the incorporation of CWS not only improves the strength but also the elastic response of sand concrete, while contributing to the sustainable recovery of ceramic waste.

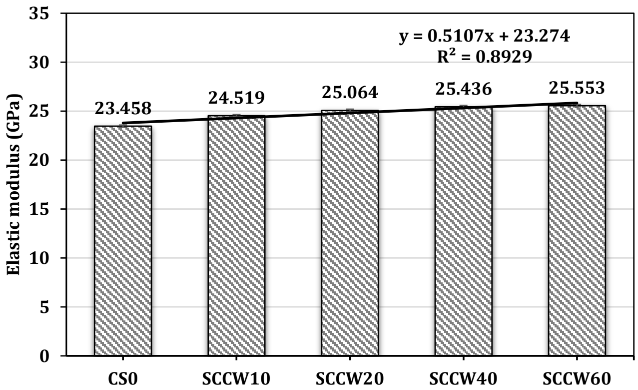

Figure 8. Elasticity modulus of the sand concrete studied

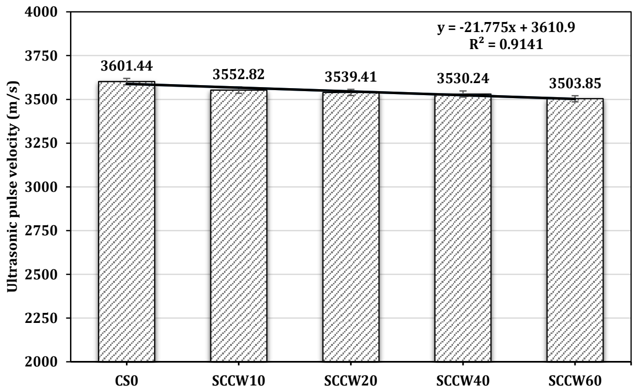

Figure 9. Ultrasonic pulse velocity (UPV) of the sand concrete studied

3.2.4 Ultrasonic pulse velocity (UPV)

Figure 9 shows the results of the ultrasonic pulse velocity (UPV) of the sand concretes studied. The reference mixture CS0 presented a UPV of 3601.44 m/s, while the mixtures incorporating CWS showed a slight progressive decrease, with a maximum reduction of approximately 2.7% for the SCCW60 mixture. This moderate decrease can be mainly attributed to the lower density of CWS compared to natural sand DS, which slightly affects the propagation characteristics of ultrasonic waves [43]. From a structural point of view, it is important to note that all measured UPV values remain above 3500 m/s, a threshold generally associated with good quality and structurally sound concrete according to standard NF EN 12504-4. Furthermore, at intermediate replacement levels between 20% and 40%, the UPV values remain near those of the reference mixture (between 3530 and 3530 m/s), while the mechanical properties reach their highest levels. This indicates an optimal substitution range in which the internal structure remains dense and homogeneous, combining favorable wave transmission characteristics with improved mechanical performance. Therefore, the observed evolution of the UPV reflects effects related to density rather than structural degradation, confirming that the incorporation of CWS up to 60% does not compromise the structural integrity of the developed sand concrete [44-46].

4. STATISTICAL ANALYSIS AND VALIDATION OF RSM MODELS

4.1 Linear regression modeling (RSM)

4.1.1 Fresh state

The statistical models at the fresh state obtained via RSM are given in Table 3. These models enable the effect of the substitution rate of DS by CWS on the fresh properties of sand concrete to be quantified. The estimated coefficients of the equations show a gradual decrease in density with increasing CWS rate, which is attributed to the lower density of the recycled material. The regression coefficient β_1 of -0.034 indicates a loss of approximately -0.034 g/cm³ for each 10% substitution, confirmed by a significant t-ratio of -4.46. In addition, the entrained air content shows a significant increase of +0.745%, due to the irregular and angular morphology of the CWS particles, which promotes air entrapment. The model predicts an increase of approximately +0.075% per 10% substitution increment, with a high t-ratio of 6.03, validating the robustness of the result. Workability shows a clear improvement with a higher CWS rate, due to better particle distribution and lower water absorption. The model indicates a gain of approximately +0.286 cm for each 10% substitution, with a t-ratio of 4.84. These effects are highly statistically significant (t-ratios > |2|) and highlight the potential of CWS to improve the fresh properties of sand concrete, while contributing to the sustainable recovery of ceramic waste.

Table 3. Statistical results of the sand concrete studied in the fresh state

	Term	Fresh Density	Air Content	Workability
Estimated coefficient	β_0	2.243	5.879	24.469
	β_1	-0.034	0.745	2.861
Standard error	β_0	0.006	0.090	0.432
	β_1	0.008	0.123	0.591
t-ratio	β_0	405.120	65.190	56.660
	β_1	-4.460	6.030	4.840
Model		$2.243 - 0.034\left(\frac{CWS-30}{30}\right)$	$5.879 + 0.745\left(\frac{CWS-30}{30}\right)$	$24.469 + 2.861\left(\frac{CWS-30}{30}\right)$

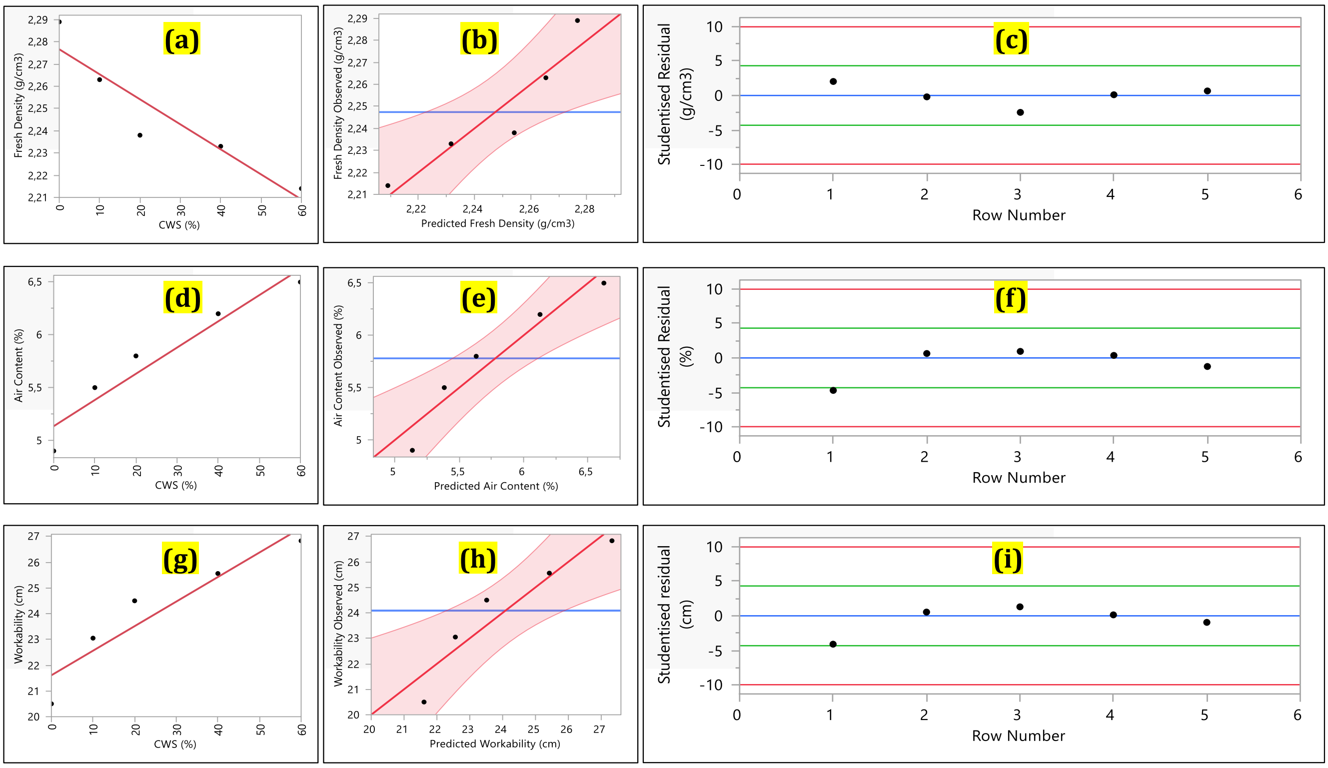

Figure 10. Validation of RSM models in the fresh state: (a, d and g) correspond to the fitting curves of fresh density, air content, and workability respectively, as a function of the CWS substitution rate, (b, e and h) correspond to the correlations between experimental and predicted data for fresh density, air content, and workability, respectively, and (c, f and i) correspond to the random distribution of residuals for fresh density, air content, and workability, respectively

Figure 10 illustrates the validation of statistical models developed using RSM for the fresh properties of sand concrete incorporating CWS. Figures 10(a), (d), and (g) show the properties determined experimentally and those predicted for fresh density, air content, and workability, respectively, as a function of the CWS substitution rate. Figure 10(a) shows a clear linear decrease in fresh density with increasing CWS content, confirming the influence of the lower specific density of CWS compared to DS. This effect is well represented by the model, as shown by the close alignment between the experimental and predicted values in Figure 10(b) [47]. The corresponding residual plot (Cf. Figure 10(c)) shows a random distribution around zero within the ± 3σ confidence limits, demonstrating the homoscedasticity and reliability of the regression fit [48].

Furthermore, Figures 10(d) to (f) indicate a positive linear relationship between air content and substitution by CWS. The increase in entrained air is clearly illustrated in Figure 10(d). The excellent agreement between experimental and predicted values in Figure 10(e) and the absence of systematic bias in the residuals in Figure 10(f) further confirm the reliability of the model.

Figures 10(g), (h), and (i) present the results for workability. The strong positive correlation between slump values and CWS rate in Figure 10(g) indicates improved consistency with higher substitution rates. Figure 10(h) compares experimental and predicted values and shows points closely aligned along the midline, confirming the good predictive accuracy of the model. The residual analysis in Figure 10(i) shows a pattern of uniform dispersion within acceptable statistical limits, indicating that the normality assumption has not been violated and confirming the adequacy of the regression model.

In general, the findings 10 confirm the excellent predictive power and statistical validity of the RSM models for the fresh properties of sand concrete. The linearity, low residual dispersion, and narrow confidence intervals prove that the models effectively describe the experimental behavior and can be reliably used to predict fresh density, air content, and workability across the entire substitution range studied.

4.1.2 Hardened state

The hardened statistical models obtained via RSM are presented in Table 4. These models enable the effect of the substitution rate of DS by CWS sand on the mechanical and elastic properties of sand concrete to be quantified. The estimated coefficients of the equations reveal a constant improvement in strength and stiffness with increasing CWS content. Compressive strength shows a significant increase of +3.10 MPa for each 10% substitution, with a very high t-ratio of 7.36, confirming the high statistical significance of the effect. In addition, flexural strength shows a marked increase of +2.46 MPa for every 10% substitution, supported by a t-ratio of 10.28, indicating an even stronger influence of CWS on the tensile performance of the composite material. Also, the dynamic modulus of elasticity (Ed) shows a moderate increase of +0.935 GPa for every 10% substitution, with a positive regression coefficient and a t-ratio greater than the critical value of |2|, suggesting that adding CWS helps improve the stiffness and overall rigidity of the material. Conversely, the ultrasonic pulse velocity (UPV) shows a slight negative variation of –40.92 m/s related to each 10% substitution, accompanied by a low but significant t-ratio.

Figure 11 shows the validation of statistical models obtained using RSM for the properties of hardened sand concrete incorporating CWS. Figures 11(a), (b), and (c) illustrate the variation in compressive strength as a function of the CWS substitution rate. A clear positive linear trend is observed, indicating that the incorporation of CWS improves compressive strength. The close alignment between the predicted and observed data (Figure 11(b)) and the random distribution of residuals around the zero line within ±3σ (Figure 11(c)) confirms the accuracy and reliability of the regression model.

Figures 11(d), (e), and (f) show the results for flexural strength. The strong positive correlation ($R^2 > 0.95$) highlights the beneficial influence of CWS on the cementitious matrix. The predictive model is highly consistent, as the experimental values follow the predicted curve within the 95% confidence interval. Analysis of the residuals (see Figure 11(f)) confirms the absence of heteroscedasticity, thus validating the homogeneity of the data set.

Figures 11(g), (h), and (i) show a decrease in ultrasonic pulse velocity (UPV) with increasing CWS rate, suggesting a slightly more heterogeneous internal structure. However, UPV values remain within acceptable limits, reflecting good compactness and mechanical integrity of the material. The observed and predicted values (Figure 11(h)) show satisfactory correlation, and the residuals (Figure 11(i)) remain randomly dispersed without systematic deviation, confirming the relevance of the statistical model.

Table 4. Statistical results of the sand concrete studied in the hardened state

	Term	Compressive Strength	Flexural tensile Strength	UPV	Ed
Estimated coefficient	β_0	32.062	8.295	3540.095	24.931
	β_1	3.104	2.456	-40.924	0.935
Standard error	β_0	0.3079	0.17451	7.7479	0.2145
	β_1	0.4215	0.2389	10.6091	0.2937
t-ratio	β_0	104.14	47.53	456.92	116.22
	β_1	7.36	10.28	-3.86	3.18
Model		$32.062 + 3.104\left(\frac{CWS - 30}{30}\right)$	$32.062 + 3.104\left(\frac{CWS - 30}{30}\right)$	$3540.095 - 40.924\left(\frac{CWS - 30}{30}\right)$	$24.931 + 0.935\left(\frac{CWS - 30}{30}\right)$

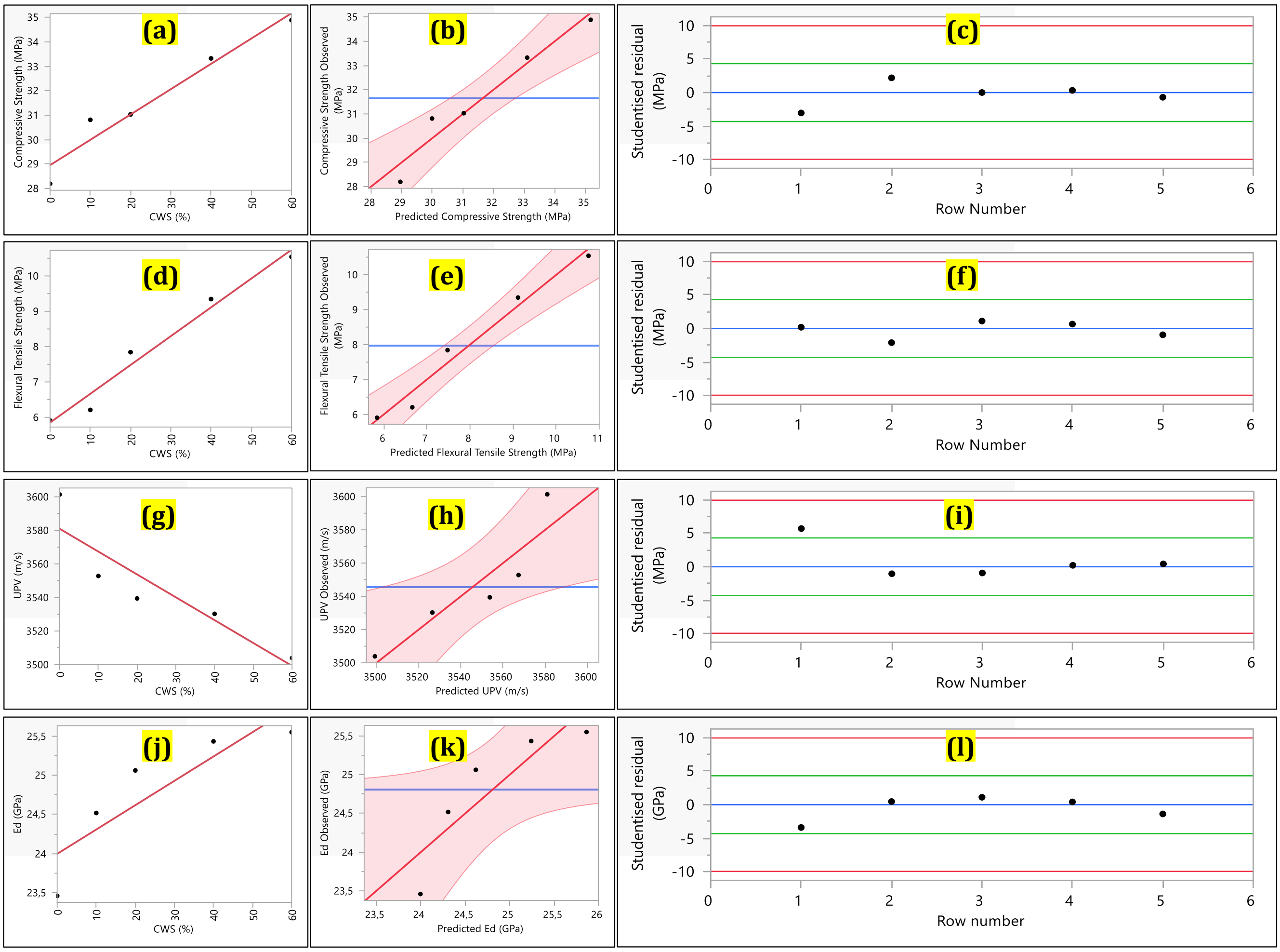

Figure 11. Validation of RSM models in the hardened state: (a, d, g, and j) correspond to the fitting curves of compressive strength, flexural strength, UPV, and Ed, respectively, as a function of the CWS substitution rate, (b, e, h, and k) correspond to the correlations between experimental and predicted data for compressive strength, flexural strength, UPV, and Ed, respectively, (c, f, i, and l) correspond to the random distribution of residuals for compressive strength, flexural strength, UPV, and Ed, respectively

Figures 11(j), (k), and (l) illustrate the model's performance for the dynamic modulus of elasticity (Ed). A slight but constant increase in Ed is observed with higher CWS incorporation. The regression curve corresponds well to the experimental data, and the residuals remain uniformly distributed, indicating that the model appears to be robust.

In general, the results presented in Figure 11 confirm the statistical robustness and goodness of fit of the RSM models applied to the hardened properties of sand concrete containing CWS. The linear relationships, the 95% narrow confidence bands, and the well-behaved residuals collectively indicate excellent predictive reliability and compliance with the fundamental assumptions of normality, independence, and homoscedasticity [47, 48]. These findings validate the models developed as effective tools for quantifying and optimizing the influence of CWS on the mechanical performance of durable sand concrete mixtures.

4.2 Significance of the models - analysis of variance

Given the importance of the CWS on the performance of the concrete in both its fresh and hardened states, a comprehensive statistical analysis was performed using analysis of variance (ANOVA). In the fresh state, the ANOVA results are presented in Table 5 and show that all the models developed are statistically significant, with p-values below 0.05. This confirms that the substitution rate of DS by CWS has a real and measurable influence on the various response variables. The coefficients of determination (R^2), which ranged from 0.869 to 0.924, indicate that the models explain approximately 87 to 92% of the total variance in the experimental data, confirming an excellent level of agreement between the predicted values and those obtained experimentally. Furthermore, the adjusted R^2, which remains close to the unadjusted R^2, confirms the robustness of the regression models and prevents any overestimation due to unnecessary explanatory variables [49].

The predictive coefficients (Pred-R^2), although slightly lower, remain within acceptable limits, confirming the satisfactory predictive capacity of the models. In addition, the root mean square error (RMSE) and the coefficient of variation (CV), which are less than 5%, provide good evidence of the high precision of the experimental data. Finally, the adequate precision values (Adeq Pr), which all exceed the recommended limit of 4, confirm a high signal-to-noise ratio in the models developed [50]. These statistical indicators collectively validate the reliability of the RSM approach for modeling and predicting the influence of CWS incorporation on the fresh properties of sand concrete [51].

Table 5. Analysis of variance (ANOVA) in the fresh states

Response	Source	Degrees of Freedom	Sum of Squares	F-value	P-value (Prob > F)
Fresh Density	Model (SSR)	1	0.002941	19.85	**0.0210**
	Error (SSE)	3	0.000444		
	Corrected Total (SST)	4	0.003385		
	R^2 = 0.869	Mean = 2.247	C.V = 1.29%;		
	Adj-R^2 = 0.825	Std. Dev =0,029	PRESS = 0.0013		
	Pred-R^2 = 0.6192	RMSE = 0.0122	Adeq Pr =6.4085		
Air Content	Model (SSR)	1	1.43007	36.38	**0.0091**
	Error (SSE)	3	0.11793		
	Corrected Total (SST)	4	1.54800		
	R^2 = 0.924	Mean = 5.78	C.V= 3.43%		
	Adj- R^2 = 0.898	Std. Dev =0,622	PRESS =0.4673		
	Pred-R^2 = 0.6981	RMSE = 0.1983	Adeq Pr = 8.6756		
Workability	Model (SSR)	1	21.1017	23.41	**0.0168**
	Error (SSE)	3	2.7046		
	Corrected Total (SST)	4	23.8063		
	R^2 = 0.886	Mean = 24.09	C.V= 3.93%		
	Adj- R^2 = 0.849	Std. Dev = 2,44	PRESS = 9.6126		
	Pred-R^2 = 0.5962	RMSE = 0.9495	Adeq Pr =6.9590		

Std. Dev: standard of deviation; C.V: coefficient of variation; PRESS: predicted residual error of sum of squares; Adj-R^2: R^2 adjusted; Pred-R^2: predicted R^2; Adeq Pr: adequate precision.

The statistical evaluation of performance in the hardened state is presented in Table 6. The ANOVA results confirm that all models are statistically significant, with p values ≤ 0.05, indicating a significant effect of the CWS substitution rate on the responses studied. The coefficients of determination (R^2) range from 0.772 to 0.972, demonstrating the models' strong ability to reproduce experimental variation. According to Schober et al. [52], R values greater than 0.9 indicate an excellent correlation between experimental and predicted results, which was the case for most models in this study.

The adjusted R^2 values remain close to the standard R^2 values, confirming the stability and robustness of the models while helping to avoid overfitting. The predictive coefficients (Pred-R^2) show an excellent predictive accuracy for compressive strength (equal to 0.8237) and flexural strength (equal to 0.9234), highlighting their high potential for use in predictive applications and formulation optimization. Conversely, more moderate and weaker predictive capabilities are observed for UPV (Pred-R^2 = 0.4873) and Ed (Pred-R^2 = 0.0822), suggesting that these parameters may be influenced by additional microstructural factors that are not accounted for in the present model.

The RMSE values, which are generally low for the main mechanical responses, confirm the accuracy of the model adjustments. The coefficients of variation (CV), although variable depending on the property considered, remain within acceptable limits for mechanical testing on cementitious materials [53]. In addition, adequate precision values greater than 4 for all models, except for Ed, indicate a good signal-to-noise ratio and reinforce the reliability of the predictive equations developed.

Finally, these results demonstrate that the RSM approach is a robust and effective tool for modeling and optimizing the mechanical and physical performance of sand concretes incorporating CWS. It allows for a quantitative assessment of the influence of recycled fine aggregates on the structural behavior of cementitious materials, while contributing to sustainable construction practices [51]. Although there are some limitations in terms of dynamic properties, which may require additional modeling or experimental refinement, the overall predictive performance of the models developed confirms the potential of RSM as a decision-making method for the design of eco-efficient concrete formulations incorporating materials from the circular economy.

Table 6. Analysis of variance (ANOVA) in the hardened states

Response	Source	Degrees of Freedom	Sum of Squares	F-value	P-value (Prob > F)
Compressive strength	Model (SSR)	1	24.8400	54.22	**0.0052**
	Error (SSE)	3	1.3743		
	Corrected Total (SST)	4	26.2143		
	R^2 = 0.948	Mean = 31.648	C.V=8.09%		
	Adj-R^2 = 0.930	Std. Dev = 2.56	PRESS = 4.6212		
	Pred-R^2 = 0.8237	RMSE = 0.677	Adeq Pr = 0.8237		
Flexural tensile strength	Model (SSR)	1	15.5538	105.64	**0.0020**
	Error (SSE)	3	0.4417		
	Corrected Total (SST)	4	15.9955		
	R^2 = 0.972	Mean = 7.968	C.V=25.0969% PRESS =		
	Adj-R^2 = 0.963	Std.Dev =1.9997	1.2259		
	Pred-R^2 = 0.9234	RMSE = 0.384	Adeq Pr =0.9234		
UPV	Model (SSR)	1	4317.11	14.88	**0.0308**
	Error (SSE)	3	870.42		
	Corrected Total (SST)	4	5187.53		
	R^2 = 0.832 Adj-R^2 = 0.776 Pred-R^2 = 0.4873	Mean = 3545.55 Std.Dev =36.0123 RMSE = 17.033	C.V= 1.016% PRESS = 2659.48 Adeq Pr =5.5484		
Ed	Model (SSR)	1	2.2538	10.13	**0.0500**
	Error (SSE)	3	0.6672		
	Corrected Total (SST)	4	2.9209		
	R^2 = 0.772	Mean = 24.81	C.V=3.45%		
	Adj- R^2 = 0.695	Std.Dev =0.8545	PRESS = 2.6808		
	Pred-R^2 = 0.0822	RMSE = 0.472	Adeq Pr =4.5790		

Std. Dev: standard of deviation; C.V: coefficient of variation; PRESS: predicted residual error of sum of squares; Adj-R^2: R^2 adjusted; Pred-R^2: predicted R^2; Adeq Pr: adequate precision.

5. CONCLUSION

This study highlights the technical and environmental potential of CWS as a sustainable alternative to natural sand in sand concrete. Experimental results showed that increasing the CWS content significantly improved the workability of fresh mixes, which increased from 21.5 cm to 26.2 cm for 60% substitution. In addition, the fresh density decreased slightly, allowing for the design of lighter concretes that can be used in non-structural or precast applications.

In the hardened state, the incorporation of CWS led to a remarkable improvement in mechanical performance, particularly at substitution rates between 20% and 40%, where compressive strength increased by about 20% and flexural strength by nearly 40% compared to the reference mixture. These gains, combined with the improvement in elastic modulus, indicate a denser and more cohesive matrix. Despite a slight reduction in ultrasonic pulse velocity (UPV), all values remained within acceptable quality limits, confirming the good structural quality of the sand concrete developed.

Regarding statistical analyses, RSM and variance analysis via ANOVA allowed the development of reliable and significant models ($p < 0.05$) with high coefficients of determination (R^2 up to 0.972). These models demonstrated strong predictive capacity, particularly for compressive strength and flexural strength, thus enabling the optimization of sand concrete containing CWS according to the desired performance. Although the predictive capacity was more limited for UPV and modulus of elasticity, the findings confirm the relevance of this approach for recycling ceramic waste and reducing the environmental impact of construction.

These results provide a preliminary indication of the potential durability of the developed material. A comprehensive assessment of long-term durability, such as resistance to sulfate attack, acidic environments, or freeze-thaw cycles, supported by specific experimental research and life cycle analysis, remains an essential prospect for future research before any large-scale structural application.

ACKNOWLEDGMENT

The authors would like to acknowledge the technical support received from the staff and facilities at the Laboratories of the Habitat and Construction (LHC-East) in Skikda, Algeria, and from the GICA Cement Company in

Skikda, Algeria.

REFERENCES

[1] Bauby, A., Florentin, D., Chatain, V. (2022). The challenge of on-site sorting of construction waste. Environnement, Ingénierie & Développement, 86: 3-13. https://doi.org/10.46298/eid.2021.8336

[2] Mechling, J.M., Diliberto, C., Braymand, S., Belhaj, E. (2023). Recycling construction and public works materials and their recycling channels. Le Recyclage, Enjeu Pour L'économie Circulaire: 289-324. https://doi.org/10.51926/iste.9162.ch12

[3] Clavier, S., Bendahmane, N., Gondran, N., Chevalier, J. (2023). Method for quantifying urban mine flows: The case of clay bricks in Ile-de-France. Environnement, Ingénierie & Développement, 88: 20-32. https://doi.org/10.46298/eid.2023.10159

[4] Rezaiguia, N., Hebhoub, H., Kherraf, L., Benhalilou, M.I. (2024). Contribution to the study of an eco-sand concrete containing recycled sands from waste granite and recycled clinker. Research on Engineering Structures and Materials, 10(4): 1609-1637. https://doi.org/10.17515/resm2024.129ma1220rs

[5] Halbach, A., Boissieu, A.D. (2022). Which data ecosystem for a BIM material passport? Literature review and prospects for future research. SHS Web of Conferences, 147: 02001. https://doi.org/10.1051/shsconf/202214702001

[6] Boutaleb, F., Boutaleb, N., Bahlaouan, B., Antri, S.E. (2020). Valorization of phosphate mining waste rock in Morocco in the manufacture of ceramic tiles. Techniques Sciences Méthodes, 3: 37-43. https://doi.org/10.36904/tsm/202003037

[7] Maghri, S.E., Yousfi, S., Essallaki, H., Bouamrani, M.L. (2022). Study of the effect of the addition of marble waste on the properties of Recycled Brick Aggregates (RBA) Concrete. Matériaux & Techniques, 110(5): 502. https://doi.org/10.1051/mattech/2022032

[8] Barreto, E.D.S., Stafanato, K.V., Marvila, M.T., De Azevedo, A.R.G., Ali, M., Pereira, R.M.L., Monteiro, S.N. (2021). Clay ceramic waste as pozzolan constituent in cement for structural concrete. Materials, 14(11): 2917. https://doi.org/10.3390/ma14112917

[9] Juan-Valdés, A., Rodríguez-Robles, D., García-González, J., De Rojas Gómez, M.I.S., Guerra-Romero, M.I., De Belie, N., Pozo, J.M.M. (2020). Mechanical and microstructural properties of recycled concretes mixed with ceramic recycled cement and secondary recycled aggregates. A viable option for future concrete. Construction and Building Materials, 270: 121455. https://doi.org/10.1016/j.conbuildmat.2020.121455

[10] Silva, D.A.E., De Melo, C.E.L. (2021). Use of ceramic material from BDW for concrete application: A review. Risco Revista De Pesquisa Em Arquitetura E Urbanismo, 19: 1-15. https://doi.org/10.11606/1984-4506.risco.2021.162069

[11] Meena, R.V., Jain, J.K., Chouhan, H.S., Beniwal, A.S. (2022). Use of waste ceramics to produce sustainable concrete: A review. Cleaner Materials, 4: 100085. https://doi.org/10.1016/j.clema.2022.100085

[12] Joshi, P., Parekh, D. (2023). Valorization of ceramic waste powder as cementitious blend in self-compacting concrete – A review. Materials Today Proceedings, 77: 1007-1015. https://doi.org/10.1016/j.matpr.2023.01.068

[13] Roig-Flores, M., Reig, L., Albero, V., Hernández-Figueirido, D., Melchor-Eixea, A., Pitarch, Á.M., Piquer, A. (2023). Utilisation of ceramic stoneware tile waste as recycled aggregate in concrete. Buildings, 13(8): 1968. https://doi.org/10.3390/buildings13081968

[14] Handel, N., Amrane, M., Mebirouk, N., Aguiar, J.B. (2025). Comparative performance of blast furnace slag, ceramic, and glass waste as supplementary cementitious additions in concrete: Experimental and machine learning analysis. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 1-28. https://doi.org/10.1007/s40996-025-01860-z

[15] Jwaida, Z., Dulaimi, A., Bernardo, L.F.A. (2024). The use of waste ceramic in Concrete: A review. CivilEng, 5(2): 482-500. https://doi.org/10.3390/civileng5020024

[16] Ocampo, M.A.A., González, A.F.R. (2023). Ceramic waste reuse and valorization alternatives: A review. Revista EIA, 20(40): 4018. https://doi.org/10.24050/reia.v20i40.1680

[17] Fnides, M., Amroune, S., Belaadi, A., Saada, K., Chai, B.X., Abdullah, M.M.S., Alshaikh, I.M.H., Ghernaout, D., Al-Khawlani, A. (2024). Modeling and optimizing the alkaline treatment process to enhance the date palm fibers' tensile mechanical properties using RSM. Journal of Natural Fibers, 21(1): 2384663. https://doi.org/10.1080/15440478.2024.2384663

[18] Patil, S., Ramesh, B., Sathish, T., Saravanan, A. (2024). RSM-based modelling for predicting and optimizing the rheological and mechanical properties of fibre-reinforced laterized self-compacting concrete. Heliyon, 10(4): e25973. https://doi.org/10.1016/j.heliyon.2024.e25973

[19] Alani, A.H. (2025). Optimizing sustainable high-performance green-concrete characteristics with minimum cement content: Experimental program. Jordan Journal of Civil Engineering, 19(1): 57-73. https://doi.org/10.14525/jjce.v19i1.05

[20] Azimi-Pour, M., Eskandari-Naddaf, H. (2020). Synergistic effect of colloidal nano and micro-silica on the microstructure and mechanical properties of mortar using full factorial design. Construction and Building Materials, 261: 120497. https://doi.org/10.1016/j.conbuildmat.2020.120497

[21] Bilondi, M.P., Ghaffarian, V., Daluee, M.A., Pakizehrooh, R., Tazik, S.H., Behzadian, A., Zaresefat, M. (2025). Experimental studies on mix design and properties of ceramic-glass geopolymer mortars using response surface methodology. Scientific Reports, 15(1): 282. https://doi.org/10.1038/s41598-024-82658-3

[22] Igunma, O.A., Erhiferhi, O.K. (2025). Response surface methodology for evaluating voids in metakaolin modified granite-granular sand densely graded asphalt concrete. Journal of Architecture and Civil Engineering, 10(5): 1-23. https://doi.org/10.35629/8193-10050123

[23] Chanvillard, G., Basuyaux, O. (1996). Une méthode de formulation des bétons de sable maniabilité et résistance fixées. Bulletin-Laboratoires Des Ponts et Chaussees, 49-64.

[24] Neville A.M. (2011). Properties of Concrete. Pearson Education Limited, Essex.

[25] Abdennaji, T.S., Tipu, R.K., Alassaf, Y. (2025). Predicting compressive and tensile strength of concrete with different sand types using machine learning. Ain

Shams Engineering Journal, 16(8): 103474. https://doi.org/10.1016/j.asej.2025.103474

[26] Duval, J. (2024). Sociologie et statistique, d'Auguste Comte à Pierre Bourdieu: Une tradition française? Revista Brasileira de Sociologia-RBS, 12.

[27] Guendouz, M., Boukhelkhal, D., Bourdot, A., Babachikh, O., Hamadouche, A. (2021). The effect of ceramic wastes on physical and mechanical properties of Eco-Friendly flowable sand concrete. In IntechOpen eBooks. https://doi.org/10.5772/intechopen.95041

[28] ElNemr, A., Shaltout, R. (2025). Rheological and mechanical characterization of Self-Compacting concrete using recycled aggregate. Materials, 18(7): 1519. https://doi.org/10.3390/ma18071519

[29] Ellatief, M.A., Abadel, A.A., Federowicz, K., Elrahman, M.A. (2023). Mechanical properties, high temperature resistance and microstructure of eco-friendly ultra-high performance geopolymer concrete: Role of ceramic waste addition. Construction and Building Materials, 401: 132677. https://doi.org/10.1016/j.conbuildmat.2023.132677

[30] Jain, P., Gupta, R., Chaudhary, S. (2022). A literature review on the effect of using ceramic waste as supplementary cementitious material in cement composites on workability and compressive strength. Materials Today Proceedings, 65(2): 871-876. https://doi.org/10.1016/j.matpr.2022.03.453

[31] Marshdi, Q.S.R., Hussien, S.A., Mareai, B.M., Al-Khafaji, Z.S., Shubbar, A.A. (2021). Applying of No-fines concretes as a porous concrete in different construction application. Periodicals of Engineering and Natural Sciences, 9(4), 999-1012. https://doi.org/10.21533/pen.v9i4.2476

[32] Nhari, R.N.R., Norazmi, N.H.M., Mohammad, W.N.S.W. (2022). Properties of concrete with the inclusion of ceramic waste as coarse aggregate. International Journal of Academic Research in Business and Social Sciences, 12(11): 1683-1693. https://doi.org/10.6007/ijarbss/v12-i11/15309

[33] Biney, E., Akortia, V.K., Kankam, C.K., Quarm, J.K., Junior, Adzakey, P. (2022). Assessing structural performance of ceramic waste as partial replacement of coarse aggregate on properties of concrete. Journal of Engineering Research and Reports, 23(12): 134-147. https://doi.org/10.9734/jerr/2022/v23i12771

[34] Rihia, C., Hebhoub, H., Kherraf, L., Djebien, R., Abdelouahed, A. (2019). Valorization of waste in sand concrete based on plant fibres. Civil and Environmental Engineering Reports, 29(4): 41-61. https://doi.org/10.2478/ceer-2019-0043

[35] Oualit, M., Irekti, A., Sarri, A. (2022). Influence of curing conditions and the alkali content on the mechanical performance of alkali-activated materials based on blast furnace slag. Matériaux & Techniques, 110(2): 202. https://doi.org/10.1051/mattech/2022017

[36] El-Hassan, K.A., Amin, M., Elsakhawy, Y., Riad, I.M. (2025). Enhancing ultra-high-performance concrete with agricultural and industrial by-products: A study on sesame oil waste ash and ceramic waste. Innovative Infrastructure Solutions, 10(7): 307. https://doi.org/10.1007/s41062-025-02121-8

[37] Joshi, T., Dave, U., Raman, S.N., Shah, V. (2025). Evaluation of strength, durability, and microstructural properties of concrete with ceramic waste aggregates. Construction and Building Materials, 491: 142733. https://doi.org/10.1016/j.conbuildmat.2025.142733

[38] Johnson Daniel, R. Sangeetha, S.P. (2023). Experimental study of the effect of ceramic waste powder on the mechanical and structural properties of concrete: A sustainable approach. International Journal of Civil Engineering, 10(10): 7-18. https://doi.org/10.14445/23488352/ijce-v10i10p102

[39] Chokkalingam, P., El-Hassan, H., El-Dieb, A., El-Mir, A. (2022). Development and characterization of ceramic waste powder-slag blended geopolymer concrete designed using Taguchi method. Construction and Building Materials, 349: 128744. https://doi.org/10.1016/j.conbuildmat.2022.128744

[40] Hashim, A.A., Anaee, R., Nasr, M.S. (2025). Improving the mechanical, corrosion resistance, microstructural and environmental performance of recycled aggregate concrete using ceramic waste powder as an alternative to cement. Ceramics, 8(1): 11. https://doi.org/10.3390/ceramics8010011

[41] Ahmad, J., Alattyih, W., Jebur, Y.M., Alqurashi, M., Garcia-Troncoso, N. (2023). A review on ceramic waste-based concrete: A step toward sustainable concrete. Reviews on Advanced Materials Science, 62(1): 20230346. https://doi.org/10.1515/rams-2023-0346

[42] Tawfik, T.A., Sičáková, A., Kuzielová, E., Kušnír, Š., Eštoková, A., Bálintová, M., Junáková, N. (2024). Sustainable reuse of waste ceramic tiles powder and waste brick powder as a replacement for cement on green high strength concrete properties. Innovative Infrastructure Solutions, 9(5): 166. https://doi.org/10.1007/s41062-024-01498-2

[43] Ray, S., Haque, M., Sakib, M.N., Mita, A.F., Rahman, M.M., Tanmoy, B.B. (2021). Use of ceramic wastes as aggregates in concrete production: A review. Journal of Building Engineering, 43: 102567. https://doi.org/10.1016/j.jobe.2021.102567

[44] Jedidi, M. (2022). Evaluation of concrete by non-destructive ultrasonic pulse velocity method. Civil Engineering and Architecture, 10(4): 1623-1630. https://doi.org/10.13189/cea.2022.100431

[45] Alshahwany, R.B., Abdulkareem, O.M., Shlla, R.D. (2024). Influence of ceramic wastes as a recycled coarse aggregate with different maximum sizes on the concrete. The Open Civil Engineering Journal, 18(1). https://doi.org/10.2174/0118741495298085240326062433

[46] Kiran, G.U., Nakkeeran, G., Roy, D., Alaneme, G.U. (2024). Optimization and prediction of paver block properties with ceramic waste as fine aggregate using response surface methodology. Scientific Reports, 14(1): 23416. https://doi.org/10.1038/s41598-024-74797-4

[47] Bouziane, A., Slimanou, H., Bouzidi, M.A., Bouzidi, N. (2025). Ceramic waste as sustainable material in self-compacting concrete: Experimental study and ANN predictive modeling. Journal of Sustainable Construction Materials and Technologies, 10(3): 2. https://doi.org/10.29187/2458-973x.1190

[48] Poonam, P., Singh, V. (2023). Response surface methodology use in optimization of concrete properties using blast furnace slag aggregate and recycled concrete sand. Research on Engineering Structures and Materials, 10(1): 111-133. https://doi.org/10.17515/resm2023.788me0614

[49] Awolusi, T.F., Ekhasomhi, A.I., Aluko, O.G., Akinkurolere, O.O., Azab, M., Deifalla, A.F. (2023). Performance evaluation of fiber-reinforced ferroconcrete using response surface methodology. Civil Engineering Journal, 9(4): 939-959. https://doi.org/10.28991/cej-2023-09-04-014

[50] Boumaaza, M., Belaadi, A., Alshahrani, H., Bourchak, M., Jawaid, M. (2023). Response surface methodology Optimization of Palm Rachis biochar content and temperature effects on predicting Bio-Mortar compressive strength, porosity and thermal conductivity. Journal of Natural Fibers, 20(1): 2162184. https://doi.org/10.1080/15440478.2022.2162184

[51] Zerig, T., Belachia, M., Aidoud, A., Meftah, N., Djedid, T., Abbas, M. (2024). Statistical analysis using the RSM approach of the physical behavior of green polymerized eco-mortar. Journal of Cleaner Production, 450: 141858. https://doi.org/10.1016/j.jclepro.2024.141858

[52] Schober, P., Boer, C., Schwarte, L.A. (2018). Correlation Coefficients: appropriate use and interpretation. Anesthesia & Analgesia, 126(5): 1763-1768. https://doi.org/10.1213/ane.0000000000002864

[53] Serifou, M.A., Jolissaint, O.S.P., Kouassi, B.R., Edjikémé, E. (2020). Physical-mechanical analysis of a rice/cement straw composite. Matériaux & Techniques, 108(2): 208. https://doi.org/10.1051/mattech/2020024

NOMENCLATURE

DS	Dune sand
CWS	Ceramic waste sand
L	Limestone filler
SP	Superplasticizer
W	Water
RSM	Response surface method
ANOVA	Analysis of variance
Y	The response (properties)
X	The independent variables of the studied factor (substitution rate)
SSR	Sum of squares regression
SSE	Sum of squares error
SST	Sum of squares total
R^2	Coefficient of determination
Adj-R^2	R^2 adjusted
Pred-R^2	Predicted R^2
Std. DEV	Standard of deviation
RMSE	Root means square error
C.V	Coefficient of variation
PRESS	Predicted residual error of sum of squares
Adeq Pr	Adequate precision

Greek symbols

β_0,β_1	The model coefficients